The Z boson a_T distribution at hadron colliders

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We provide a theoretical study of a novel variable introduced in Ref. [1] to study the transverse momentum of the Z boson at hadron colliders. The variable we consider has experimental advantages over the standard p_T distribution enabling more accurate measurement at low p_T. We provide an all orders perturbative estimate for this variable at the next-to–leading logarithmic accuracy and compare the results to those for the standard p_T distribution. We test our resummation, at the two-loop level, by comparing its expansion to fixed-order perturbative estimates and find agreement with our expectations.

1 Introduction

The transverse momentum p_T of lepton pairs (or equivalently that of gauge bosons which decay to lepton pairs) produced in hadron-hadron collisions has been one of the most actively studied variables in QCD phenomenology over several decades. In spite of sustained activity in this area it remains a subject of vital importance and interest. An accurate understanding of the production rates and p_T spectra of the W and Z boson can play a role in diverse applications such as luminosity monitoring at the LHC to the measurement of the W mass and most importantly perhaps in the search for new physics which may manifest itself for instance in the decay of new gauge bosons to lepton pairs.

Moreover such spectra have been a source of considerable information on QCD dynamics. Of particular interest here is the low p_T region where the resummation of logarithmically enhanced terms reflects an understanding of QCD to all orders in the soft/collinear limit. The low p_T region is also of interest in constraining the non-perturbative "intrinsic k_t" which is relevant in many other hadron collider observables. The p_T spectrum is consequently also of immense use in the tuning of Monte Carlo event generators both for the shower parameters and the intrinsic k_t component. It is therefore clear that as accurate a measurement of the p_T spectrum as possible is desirable especially at low p_T. However comparatively large experimental errors have somewhat impacted conclusions about the low p_T region, which have thus not been optimal.

An observable that may offer experimental advantages over the p_T variable has been suggested in Ref. [1]. The variable in question is simply the component of the p_T distribution transverse to an axis also defined using the lepton transverse momenta. This component, called the a_T can be measured more accurately than the longitudinal component a_L and hence than the overall $p_T = \sqrt{a_T^2 + a_L^2}$ [1]. Consequently the phenomenology of the a_T variable assumes some importance.

In the current article we provide one of the most important ingredients necessary for an accurate investigation of the a_T variable over the full range of measured values, the resummation of logarithms in a_T up to the next-to–leading logarithmic (NLL) accuracy. We

shall in forthcoming work combine these estimates with fixed-order results and include non-perturbative effects to obtain a state of the art prediction. The resummation that we carry out involves some important differences from the classic p_T resummation formalism [2, 3], which we explain.

2 The a_T distribution

To calculate the a_T distribution at low a_T one first needs to obtain the dependence of the observable on the momenta of soft emitted gluons. Denoting the transverse lepton momenta by $\vec{p}_{t1}$ and $\vec{p}_{t2}$ we define the "thrust" axis as in Ref. [1]

$$\hat{n} = \frac{\vec{p}_{t1} - \vec{p}_{t2}}{|\vec{p}_{t1} - \vec{p}_{t2}|}. \tag{1}$$

Considering the emission first of a soft gluon with transverse momentum k_t, one obtains that the a_T with respect to the above defined axis is simply

$$a_T = k_t |\sin\phi| + \mathcal{O}\left(k_t^2\right), \tag{2}$$

where at NLL accuracy we can neglect the order k_t^2 correction, while the usual p_T variable is just given by $p_T = k_t$ and ϕ is the angle between the soft gluon and the thrust axis in the plane transverse to the beam. At all orders the above result generalises to

$$a_T = \left|\sum_i k_{ti} \sin\phi_i\right| = \left|\sum_i k_{xi}\right| . \tag{3}$$

The most noteworthy aspect of the above result is that the a_T variable depends on the sum over a *single* component of soft gluon momenta (along say the x axis as indicated above). This is different from the p_T variable which at all orders is the two-dimensional vector sum of individual gluon momenta $p_T = |\sum_i \vec{k}_{t,i}|$. The resummation of observables involving a one-dimensional sum has been encountered before (see e.g. Refs. [4, 5, 6]) and we employ the formalism detailed there to arrive at our result quoted in the following section.

3 Resummed result

Here we quote the NLL resummed result for the a_T distribution. As for the p_T, it involves resummation in impact-parameter or b space which is the Fourier conjugate of k_t space and the resummed result takes the form

$$\Sigma_N(a_T) = \sigma_0(N)\, W_N(a_T)\,, \tag{4}$$

where Σ denotes the cross-section for events below some fixed value a_T (i.e the differential cross-section integrated over a limited range from 0 to a_T). For simplicity we have chosen to express our result in moment (N) space conjugate to $\tau = M^2/s$, with M^2 the mass of the lepton pair and where σ_0 is the Born cross-section. The function $W_N(a_T)$ contains the resummation of large logarithms in b space and reads

$$W_N(a_T) = \left(1 + C_1(N)\,\bar{\alpha}_s\right) \frac{2}{\pi}\int_0^\infty \frac{db}{b}\sin(b a_T) e^{-R(b)}. \tag{5}$$

The NLL b space resummation gives rise to the exponential of $R(b)$, the "radiator", precisely as in the standard p_T resummation. The difference with the p_T distribution arises from the $\sin(ba_T)$ function that represents the conservation of a single component of transeverse momentum. This is in contrast to the function $J_1(bp_T)$ that one encounters in p_T resummation, which represents conservation of both components of transverse momentum, relevant in that case. Explicit computation reveals that, within NLL accuracy, the radiator $R(b)$ in the above case turns out to be identical to that for the p_T variable so all differences are due to the presence of the $\sin(ba_T)$ as opposed to a Bessel function. The term $1 + C_1\bar{\alpha}_s$ represents a multiplicative correction which can be obtained by carrying out a full leading-order calculation (here $\bar{\alpha}_s = \alpha_s/2\pi$).

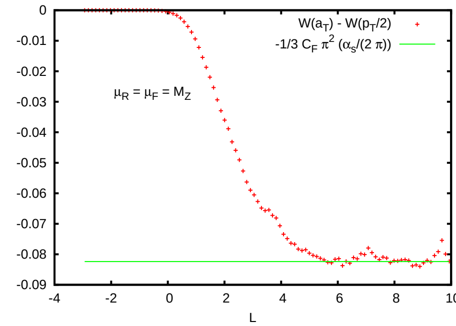

Figure 1: The difference between the integrated cross-sections for a_T and $p_T/2$ at leading order in α_s. The green line is our expectation for large positive L and the red data points are the result from MCFM.

The main difference of the above result from the p_T distribution will be the absence of a Sudakov peak in the final result for the a_T differential distribution with the result continuously rising to a constant value at $a_T = 0$. The absence of the Sudakov peak is due to the fact that the one-dimensional cancellation of a component of the $\vec{k}_{ti}$ is the dominant mechanism for producing a low a_T rather than Sudakov suppression. This is not true in the case of the p_T until very low values of p_T beyond the Sudakov peak and hence the formation of a peak in that case.

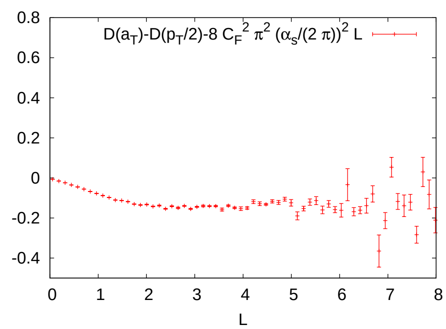

Figure 2: The difference between MCFM and our theoretical estimate for the difference in the distributions for a_T and $p_T/2$. The result seems to be consistent with the expectation of an asymptotically flat distribution.

4 Comparisons to fixed order estimates

Here we compare our predictions to those from fixed order Monte Carlo computations from the code MCFM [7]. To this end we expand Eq. (5) to order α_s^2. After noting that the result closely resembles the analogous result for the p_T distribution with the substitution $a_T \to p_T/2$ it proves most convenient to provide our predictions for the difference between the distributions for a_T and $p_T/2$. Up to the two-loop level we predict for this difference

$$W(a_T) - \tilde{W}\left(\frac{p_T}{2}\right)|_{\frac{p_T}{2}=a_T} = -\frac{1}{3}\pi^2 C_F \bar{\alpha}_s + 4\pi^2 C_F^2 \bar{\alpha}_s^2 L^2 + \mathcal{O}(\alpha_s^2 L). \tag{6}$$

In the above $\tilde{W}$ denotes the integrated event fraction for the p_T variable, which is widely available in the literature ($\bar{\alpha}_s = \alpha_s/2\pi$ and $L \equiv \ln M/a_T$).

We can test our resummation for the a_T variable by comparing the above result to the fixed-order computation from the program MCFM. At the leading order in α_s we would expect the difference between the integrated cross-sections for a_T and $p_T/2$ to tend to a constant at low a_T whose value is predicted in Eq. (6). That this is indeed the case can be seen from Fig. 1 where at large (positive) L the result from MCFM tends to our expectation. Likewise at NLO accuracy we plot in Fig. 2 the difference between MCFM and the expectation of Eq. (6) (for the differential distribution, i.e. the derivative with respect to L, $D(a_T) - \tilde{D}(p_T/2)|p_T/2 = a_T$ of Eq. (6)). The result should tend to a constant at large L and we see evidence for this in Fig. 2.

5 Conclusions

In this article we have provided a resummation of the a_T distribution to NLL accuracy. We have cross-checked our result by checking its expansion against MCFM. In forthcoming work we shall aim to match the resummed result to fixed-order results from MCFM and include non-perturbative effects in order to have a complete prediction for comparison to experimental data.

References

[1] M. Vesterinen and T.R. Wyatt, Nucl. Instrum. Meth **A602** 432 (2009), arXiv:0807.4956 [hep-ex].

[2] Y.L. Dokshitzer, D. Diakonov and S.I. Troyan, Phys. Lett. **B79** 269 (1978).

[3] J.C. Collins, D.E. Soper and G. Sterman, Nucl. Phys. **B261** 104 (1985).

[4] A. Banfi, G. Marchesini and G.E. Smye, JHEP **0204** 024 (2002), arXiv:hep-ph/0203150.

[5] A. Banfi and M. Dasgupta, JHEP **0401** 027 (2004), arXiv:hep-ph/0312108.

[6] A. Banfi, M. Dasgupta and Y. Delenda, Phys. Lett. **B665** 86 (2008), arXiv:0804.3786 [hep-ph].

[7] J.M. Campbell and R.K. Ellis, Phys. Rev. **D 65** 113007 (2007), arXiv:hep-ph/0202176.